Li-Ion, Ultra-capacitor Based Hybrid Energy Module

Dr. Zaher Daboussi[1], Anil Paryani[2], Gus Khalil, Dr. Henry Catherino, Sonya Gargies[3]
AeroVironment, Inc. 1960 Walker Ave., Monrovia CA, 91016

Ultra-capacitors in multi kilo-farad ranges are now starting to be considered as alternatives or complimentary to batteries for products ranging from toys to hybrid vehicles as well as for space applications. Combining their superb specific power of 2-5kW/kg, high efficiency and very long cycle life with the high energy density of Li-Ion batteries, practical solutions to a variety of applications can be foreseen. To determine the optimum utilization of ultra-capacitors in applications where high power density and high energy density are required, an optimized Li-Ion/Ultra-capacitor Hybrid Energy Module (HEM) is presented in this paper. The optimized HEM takes into account both the power profile of the application and the power and energy densities of available energy and power devices. Finally, this paper presents a simulation and some experimental results.

1. Introduction

With their very high power densities and low-to-moderate energy densities, ultra-capacitors are seriously considered as an alternative to or complimentary to batteries. Depending on the required energy densities, the life cycle and the cycle overall efficiency, commercially available ultra-capacitors are expected to play a very important role in automotive, aerospace and military applications. For automotive start-stop operations, also known as belt-driven alternator starter (BAS), ultra-capacitors are being considered as a candidate to help extend the cycle life of the vehicle 12/24V batteries that are subjected to a very aggressive power profile. In consumer products such as copier machines, ultra-capacitors are already utilized as a source of energy used to shorten the warm up time of copiers hence eliminating the need to increase the power rating of their utility connection. In heavy-duty vehicle applications such as refuse trucks, ultra-capacitors are considered as a part of a hybrid energy system (HES) solution aiming at reducing emissions and improving fuel economy.

Clearly, ultra-capacitors are not meant to rival batteries as an energy storage device. However, as a power device ultra-capacitors are capable of supplying and absorbing short, high power pulses more efficiently than batteries. By combining batteries and ultra-capacitors as a hybrid energy system, tangible benefits can be realized. The benefits of a HES must obviously outweigh the system complexity introduced.

For a given hybrid energy system, the ratio of batteries to ultra-capacitors depends largely on the power profile seen by the energy storage system. This paper describes a hybrid energy module (HEM) currently being developed by AeroVironment, Inc. First, and as a part of this effort, the power profile is defined. Based on the power profile as well as other system requirements a HEM configuration is then selected. To optimize the HEM and quantify its benefits, dynamic simulation of the hybrid energy module is performed. To assess the cycle life benefits of the HEM, testing is performed and finally the results of simulations and the testing are discussed.

---

[1] Principle Power Electronics and Control Engineer, AeroVironment, Inc. Energy Technology Center, 1960 Walker Ave., Monrovia, CA 91016
[2] Senior Energy Storage Engineer AeroVironment, Inc. Energy Technology Center, 1960 Walker Ave., Monrovia, CA 91016
[3] US Army RDECOM-TARDEC

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **11 JUN 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED
4. TITLE AND SUBTITLE **Li-Ion, Ultra-capacitor Based Hybrid Energy Module**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **; ; ; ; Khalil /GusCatherino /Dr.HenryGargies /SonyaDaboussi /Dr.ZaherParyani /Ani**		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AeroVironment, Inc. 1960 Walker Ave., Monrovia CA, 91016**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **TACOM TARDEC**		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited.**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**11**	

2. Selection of Power Profile

The power profile chosen in this application is aimed towards hybrid electric vehicle applications. There are three main drive configurations for electric and hybrid electric ground vehicle that are likely to influence the power and the energy profile required from the energy storage system used in these vehicles.

The three configurations and their projected specific power and energy are shown in Figure 2-1. They consist of the following:

1. Charge Sustaining HEV profile (CS-HEV)
2. Charge Depleting HEV profile (CD-HEV)
3. Pure Electric Vehicle profile (EV)

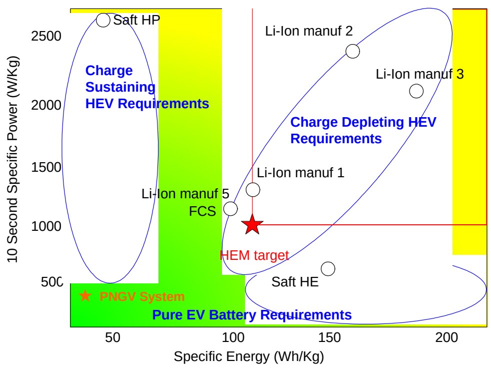


Figure 2-1 Energy and power requirements for different mode of operation

As shown in Figure 2-1, the CS-HEV is characterized with a high specific power and low specific energy requirement. The Toyota prius battery pack is one example of CS-HEV. The charge depletion HEV profile CD-HEV, on the other hand, which also is known as plug-in hybrid, is characterized with high specific power and medium specific energy. With respect to the EV profile, since typically the main driver is range, such profile is therefore characterized with higher specific energy and lower specific power. From Figure 2-1 it is clear that if tangible fuel economy benefits are going to be realized with the CD-HEV, i.e., plug in hybrid, though requirements on the energy storage will be imposed.

For this effort, the power profile selected is a modified power profile based on the USABC Battery Test Program developed by the FreedomCAR consortium previously known as the Partnership of New Generation of Vehicles (PNGV) program. The reason for selecting PNGV power profile as a basis is because it is the only recognized standard available for hybrid electric applications.

The modifications made to the PNGV profile to meet the Hybrid Energy Module (HEM) requirements are shown in Table 2-1 and Table 2-2. The new profile also reflects the power profile requirements for charge depletion HEV.

Table 2-1

	PNGV	HEM
System specific energy (Wh/kg)	15	70
System specific power (W/kg)	450 (18 sec)	700 (2 sec)

As shown in Table 2-1 and in Figure 2-2 the profile consists of three modes

1. The slow charge cycle
2. The Dynamic Stress Test (DST) cycle
3. The PNGV Recharge cycle

In Table 2-2 a brief description of each cycle is provided.

Table 2-2

Step	Mode	End SOC	Time	Dch Ah Throughput
1. Slow Charge	C/2 – 4.05V	~80%	120 Minutes	0
2. Rest	10 Minutes	~80%	10 minutes	0
3. DST	8 Cycles	~30%	48 Minutes	1.12
4. PNGV Recharge	35 Cycles	~50%	56 Minutes	1.05
5. CV Clamp	1.9A 3.80V 10 minutes	~50%	10 Minutes	0
6. DST	3 Cycles	~30%	18 Minutes	.42
7. Go to Step 4	Repeat 4 times		336 Minutes	2.59
Total			**~10 Hours**	**5.18**

~8 equivalent 80% DOD cycles / day

After 2 months, ~480 cycles will be completed

Figure 2-2 depicts the HEM desired state of charge resulting from the PNGV modified profile. As shown in this figure there are 5 sub-cycles. The main cycle starts with a slow off-load charging typical of plug in hybrid. Each of the subsequent 5 sub-cycles consists of 4 recharge cycles and 4 DST cycles interrupted by a 10 minutes of CV clamp period. In every cycle there are ~8 equivalent 80% DOD.

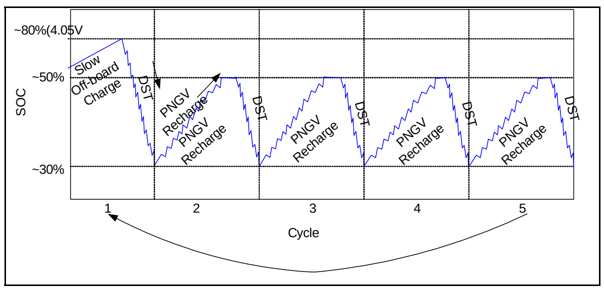
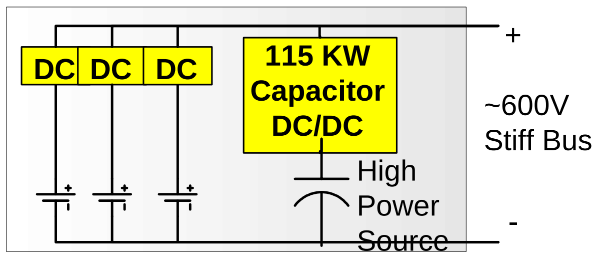
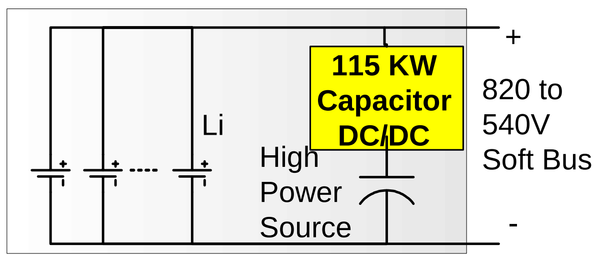


Figure 2-2 DST and PNGV recharge profiles

3. System configuration

A hybrid energy system can be implemented in many different configurations. Table 3-1 reflects 2 possible configurations. Also Table 3-1 lists some of the advantages and disadvantages of each configuration.

Table 3-1

Configuration	Topology	Merits	Demerits
Dual DC/DC		• Flexible controls for energy management • Overcharge protection • Charge balance	• Higher cost than Single DC/DC • Slightly more weight
Single DC/DC		Lower cost than Dual DC/ DC	• Complicated redundancy design. • No overcharge protection

For this effort, the dual dc-dc configuration was selected. The complete packaged HEM will have the following performance targets:

- *900 W/Kg of power density*
- *70 Wh/kg of energy density*
- *>5 year life*
- *Operate in temperature conditions as low as –40deg-C and as high as +40deg-C*
- *Cost competitive*
- *Redundant capability*
- *Safe – inherently impossible to overcharge or over discharge*
- *Programmable voltage output*

4. Simulation and optimization

To optimize the HEM module, a Matlab/Simulink model was constructed for this effort. The main blocks of the model are shown in Figure 4-1. The simulation model consist of:

1. A Battery pack module/Ultra Cap pack module
2. Power profile module
3. Power Management module
4. Ultra-capacitors and Battery power regulator module

A brief description of each module is given in the subsequent sections.

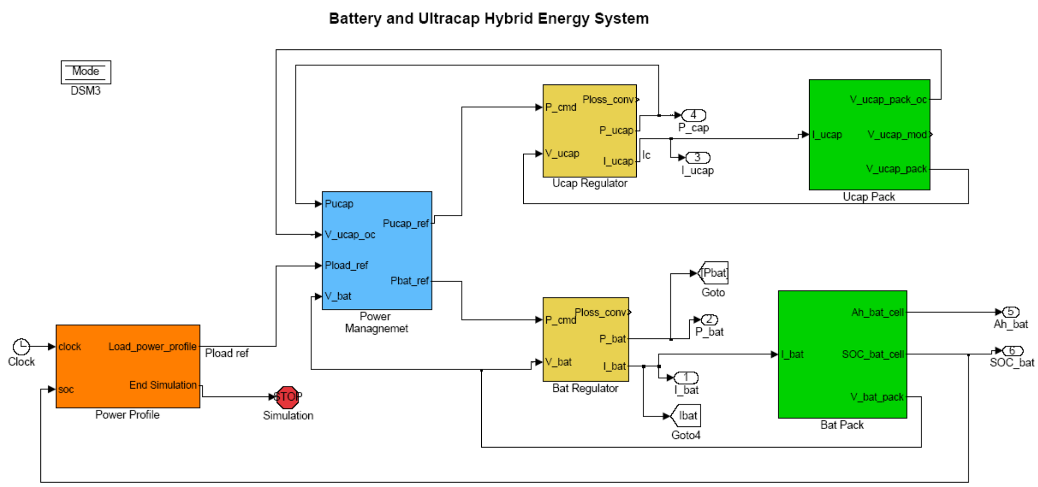


Figure 4-1 HES Matlab/Simulink Model

1. Batteries and ultra-capacitors modules

The battery and ultra-capacitor models used are shown in Figure 4-2, and Figure 4-3.

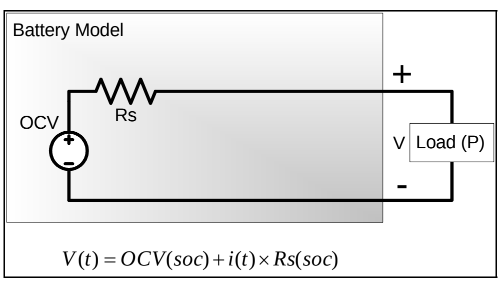


Figure 4-2 Battery Model

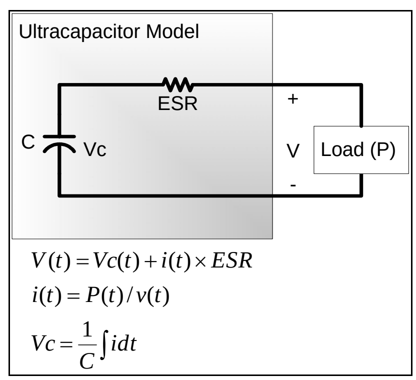


Figure 4-3 Ultra-capacitor Model

The simplified battery and ultra-capacitor models used are sufficient for examining the gross effect of the energy management strategy on voltages, currents and state of energy of these devices for a given power profile.

2. Power profile module

The DST mode and the PNGV recharge profiles described in section 2 and shown in Figure 4-4 were generated in this block. The switching between these two modes is determined based on the battery state of charge SOC. Above 50% SOC the DST mode is selected and below 30% soc the PNGV recharge mode is selected.

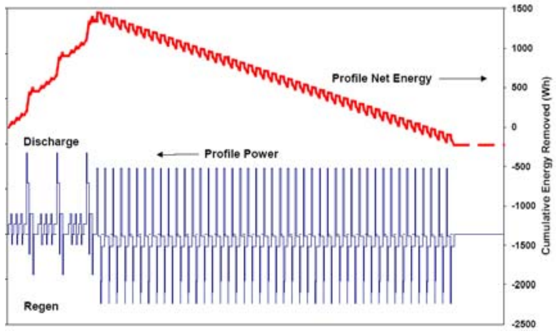


Figure 4-4 Simulink Power Profile

3. *Power Management Module*

A unique power management algorithm was implemented in this module. The algorithm strategy is outlined below:

I. During discharge mode

a. Under large load condition:

i. The batteries will supply the load until the battery current reaches a given battery current threshold I_{bat_th}.

ii. If the load is larger than what the battery can handle, the ultra-capacitors will supply the difference.

iii. If the ultra-capacitors reach its minimum allowable voltage, the batteries will provide the load up to I_{bat_max} or V_{bat_min} before the load is starved from power.

b. Under small or no load condition:

i. The battery will be used to charge the ultra-capacitors up to I_{bat_th} if ultra-capacitors can accept energy.

II. During charge mode

a. The ultra-capacitors will absorb the regeneration power until the capacitor voltage reaches its max level. At that point, the battery should absorb the remaining power.

If the regeneration power is greater than what the ultra-capacitors and battery combined can absorb, regeneration power will be limited.

4. *Ultra-capacitors and Battery power regulators*

The battery and ultra-capacitor regulator modules are identical. Figure 4-5 depicts the regulator structure. The power regulation is a PII (proportional with double integration). The regulator control objective is to track the power command by impressing the necessary current in the energy storage device. The power regulator has built-in provisions to provide protection by limiting the voltages and currents of the energy storage devices, therefore simulating protections normally required to ensure that the devices absolute terminal ratings are not exceeded.

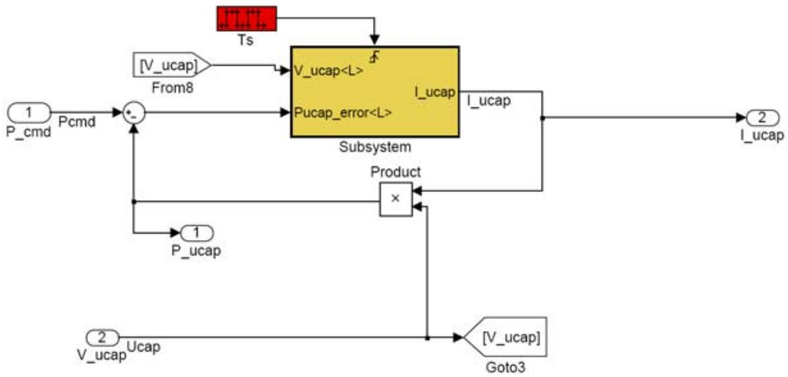


Figure 4-5 Power Regulator Module

5. Simulation results

Two cases are presented here to demonstrate the effectiveness of an ultra-capacitor based HEM. The first case is a battery only case where the batteries are subjected to the full power profile. The second case is battery plus ultra-capacitors HEM using the dual dc configuration shown in section 3. For both cases the load power profile is identical. The two cases are discussed next.

Case 1: Battery only configuration

In Figure 5-1 trace 1 displays the load profile. Trace 2 displays the Li battery cell voltage and the battery safe limits, e.g., 4.1V. Trace 3 displays the battery cell current and Trace 4 displays the battery state of charge. The rms value of the battery current (trace 3) was calculated to be 1.98Arms.

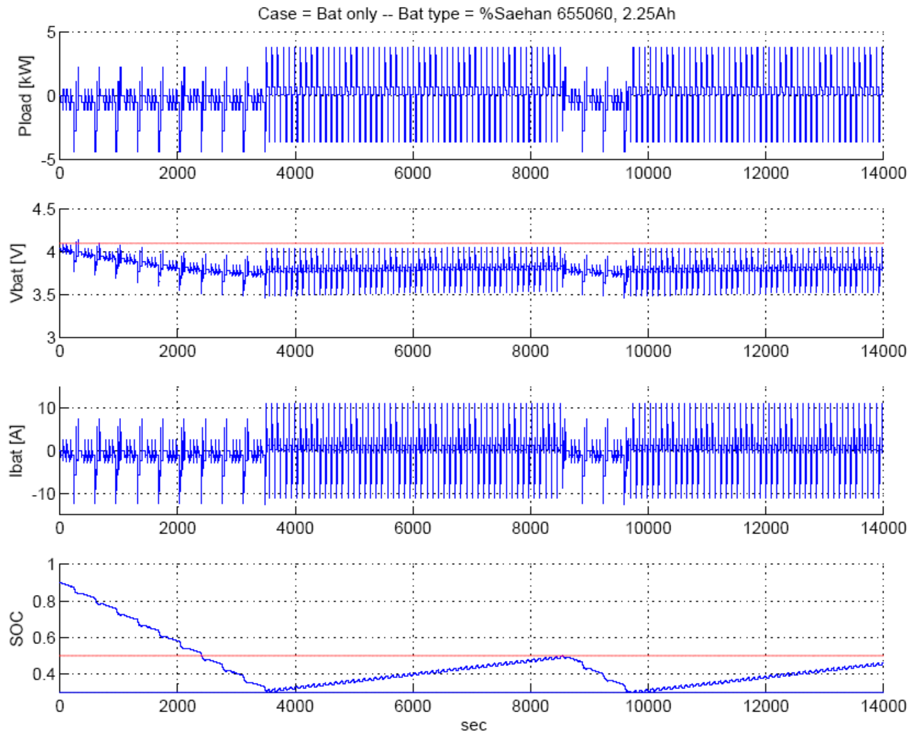


Figure 5-1 Battery only case, rms current 1.98Arms

Case 2: Battery and ultra-capacitors configuration.

The simulation result of this configuration is shown in Figure 5-2. Trace 1 displays the load profile. Trace 2 displays the battery cell voltage and the voltage upper safe limits, e.g., 4.1V. Trace 3 displays the battery cell current where Trace 4 displays the battery state of charge. The rms value of the battery current (trace 3) for this case was calculated to be 0.98Arms.

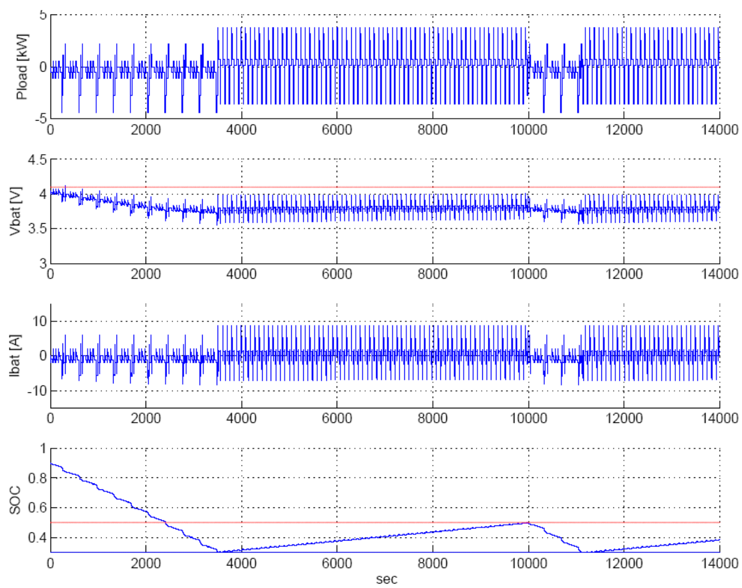


Figure 5-2 Battery plus ultra-cap simulation traces

Figure 5-3 trace 1 displays the ultra-capacitor pack's voltage with the upper and lower limits. The ultra-capacitor pack consists of 16, 700F ultra-capacitors configured in series. Trace 2 displays the ultra-capacitor pack's current. Trace 3 displays the upper and lower current limits set by the ultra cap regulator. Trace 3 clearly shows how the ultra-capacitors voltage upper/lower voltage limiter is being utilized.

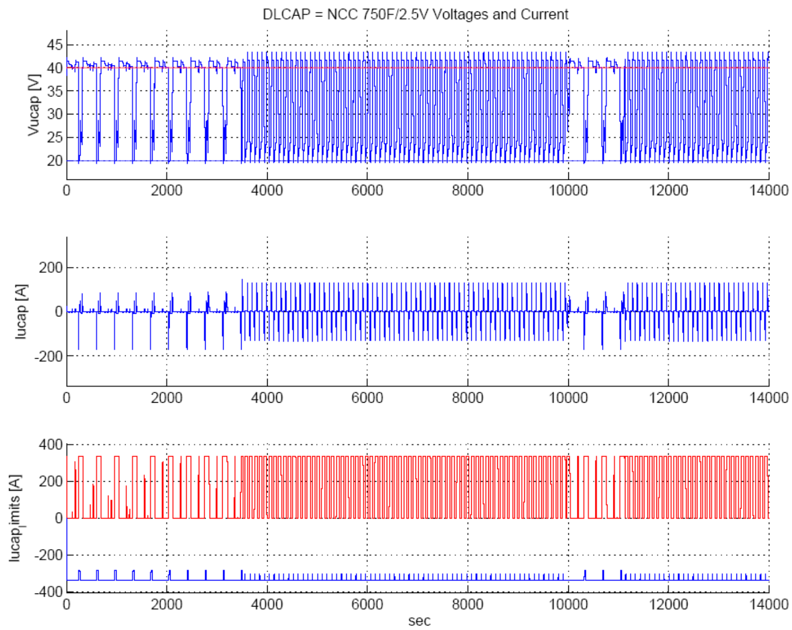


Figure 5-3 Battery plus ultra-cap simulation traces

A. Simulation discussion and conclusion

By comparing the results of case 1 and case 2 a couple of observations can be made

1. In case 1, we observe that the battery cell voltage was higher than in case 2. This is expected since the battery currents in case 2 are lower.
2. In case 1 the calculated value of the battery rms current during charge and discharge cycle was 1.98 Amps where in case 2 it was 0.98 Amps . This represents a reduction of approximately 50%!

From the above observations it can be deduced that the ultra caps helped the battery in two ways:

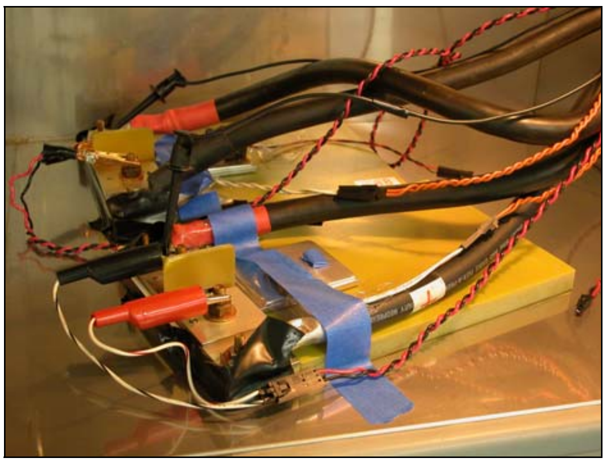
1. Reducing the battery rms current by approximately 50% and since the main battery losses are due I^2R, this results in approximately 75% reduction in battery losses. This is a significant result considering that the thermal condition of batteries is key in determining their cycle life performance.
2. By reducing the battery cell voltage and preventing it from exceeding 4.1 V, a significant safety margin is added since over-charging Li-Ion could lead to catastrophic failures.

The above benefits come with the added weigh and complexity of the additional ultra-capacitors devices. The obvious alternative is to add more batteries to the system to reduce the current rms and prevent the battery cell voltage from exceeding its upper limit. For a given application and a given power profile a tradeoff must be carried out before determining the better approach. For a complete tradeoff analysis battery cycle life testing must be determined. This is discussed in the following section.

6. Life cycle testing results and conclusion

Since the life cycle performance of battery cells varies significantly with manufacturing processes, material, environmental elements and utilization, it is very difficult to model battery cells' life cycle performance accurately. Testing battery cells using prescribed power profiles is the most effective way to determining life cycle.

To evaluate the benefits of the ultra-capacitor based HEM, life cycle testing was performed using a selected Li-Ion cell. The cell was subjected to two power profiles: battery only power profile, i.e., case 1, and battery plus ultra-capacitor, i.e., case 2.



The picture to the left shows the Li-Ion cells under test. One Li-Ion cell was subjected to case 1 power profile and the other Li-Ion cell to case 2. The testing was conducted simultaneously using AeroVironment, Inc. dual channel ABC-150 power processing systems.

For cell voltage and current monitoring AeroVironment, Inc. Smart Guard™ data acquisition modules were used

The results of the life cycle test are shown in Figure 6-1. The battery critical parameters that were compared to determine that net effect of each power profile are:

1 The cell capacity (Ah)
2 The cell resistance (mOhm)
3 The cell 10 sec, kW/kg discharge rate at 50% SOC

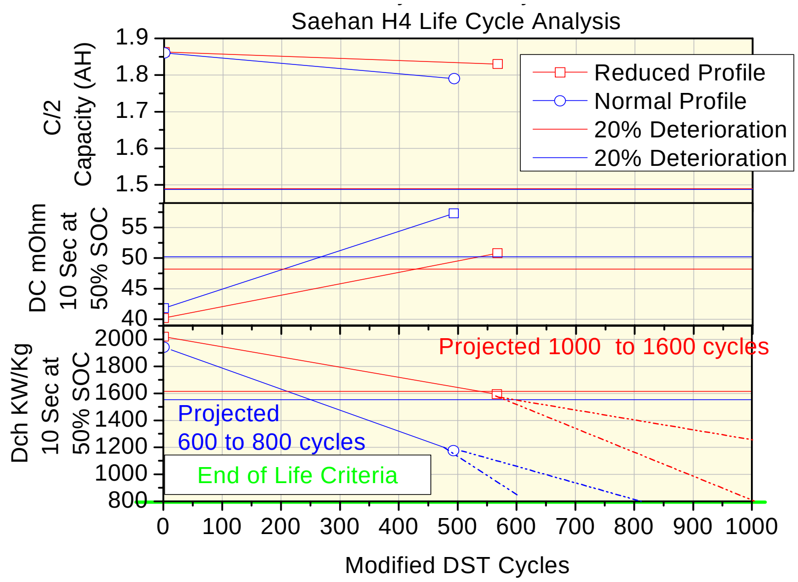


Figure 6-1 Battery Life Cycle Analysis

In the figure above the normal profile refers to case 1 and the reduced profile to case 2. The following are the observations on the test results

1. 20% deterioration in the cell resistance and the discharge power density occurs after 270 DST of normal profile cycles verses 540 of reduced profile cycles.
2. No significant cell capacity fade was observed between profiles.

From the above, it is estimated that under the best-case scenario an ultra-capacitor based HEM will more than double the battery's cycle life, i.e., by 160% (1600 cycles vs. 600 cycles). Under the most conservative scenario, the ultra-capacitor based HEM will improve the battery cycle life by about 25% (1000 cycles vs. 800 cycles).

In conclusion, under this effort there has been a significant contribution to the understanding of ultra-capacitor based hybrid energy modules. The benefits of ultra-capacitor based HEM were quantified in terms of performance as well as life cycle. More work is underway to construct a 15kW, 1kWh hybrid module to further demonstrate the operation, the life cycle performance and the feasibility of building them in a cost effective manner.

Acknowledgments

AeroVironment, Inc. would like to express its appreciation to Mr. Gus Kahlil, Dr. Henry Catherino and Miss Sonya Gargies of TARDAC for their support during the phase I of this SBIR program, and for their continuing support during Phase II.